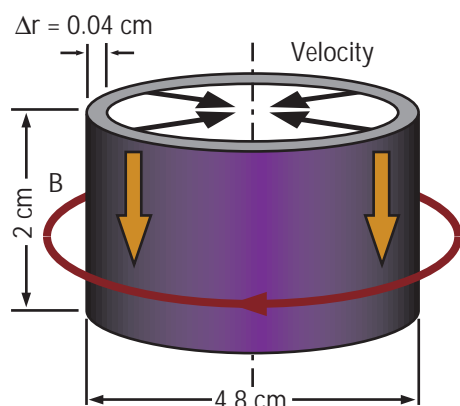


## High-Energy-Density Physics at the Pegasus II Pulsed-Power Facility

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**Fig. 1** Diagram of a standardized aluminum liner for Pegasus II. As the Marx bank discharges, electrical current flows in the outer skin of the liner creating a strong magnetic field ( $B$ ). The interaction of the current and magnetic field produces forces that implode the liner. In some experiments, a target is located inside the liner.

### Introduction

The Pegasus II pulsed-power facility is used to conduct a variety of high-energy-density experiments that have applications to the nuclear weapons programs as well as to basic science. Forty-seven experiments were conducted at the facility during calendar years 1997 and 1998. Its unique capability of delivering strong, converging, shock-driven or adiabatically driven compressions in a macroscopic volume, combined with a well-developed suite of permanent and shot-specific diagnostics, have allowed physicists to conduct experiments that are providing important data to the weapons physics community. These data are currently being used to guide the development of particular models of material behavior in high-energy-density regimes and also to validate computer codes used to predict material behavior in these regimes.

The experiments performed at Pegasus II fall under three broad categories: hydrodynamic instabilities, material properties, and basic science and technology. Below, we present an overview of the facility and a discussion of each category with representative examples, and we conclude with a brief overview of the physics agenda for Atlas, the follow-on facility to Pegasus II that is now under construction.

### Facility Overview

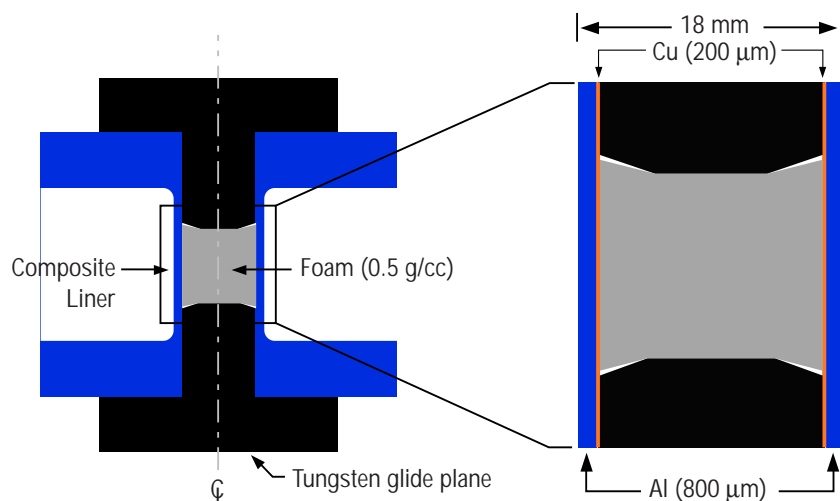
The Pegasus II facility consists of 144 capacitors arranged in a two-stage Marx bank with a maximum energy-storage capacity of 4.3 MJ. The Marx bank has a maximum erected voltage of 100 kV generating peak electrical currents as high as 12 MA in cylindrical inductive loads.

A typical load, also known as a liner, is shown in Fig. 1. It is made from 1100-series aluminum and is designed such that the inner surface remains solid during the course of the experiment while the liner is heated resistively by the electrical current. Experiments are conducted with or without targets in the interior depending on the nature of the experiment. The dimensions shown in Fig. 1 are for a standardized liner. Pegasus II can deliver  $\sim 0.5$  MJ of kinetic energy to the 4.8-cm-diameter, 3.2-gram liner. The impact of this liner on an internal target with a diameter of a few centimeters results in shock pressures of 100–500 kbar in the target at liner velocities of  $\sim 3$  km/s when driven under typical Pegasus II operating conditions. The liner's dimensions and composition are modified to meet the needs of the particular experiment. For example, we can apply a layer of dense material to the liner's inner surface to increase the ram pressure upon impact with a target. For a majority of experiments the liners and targets are constructed at the Los Alamos Target Fabrication Facility operated by the Materials Technology/Coatings and Polymers Group (MST-7).

A panoply of well-developed diagnostics is available for Pegasus experiments. Core diagnostics, those used on every shot, include current probes that measure the current pulse delivered to the liner and flash x-ray radiography with side views of the liner-target assembly. Different shot-specific diagnostics are deployed depending on the nature of the experiment and can include time-resolved pyrometry, particle holography, multiple-frame flash radiography along the liner-target cylindrical axis, laser backlighting, visible imaging of the target, optical pins, and VISAR (an acronym for “velocity interferometer system for any reflector”).

### Hydrodynamic Instabilities

An important area of research at the Laboratory is the study of the hydrodynamic flow of materials under extreme conditions. Of particular interest are the dynamics of instabilities that can be induced in hydrodynamic flow. Results of experiments are used to guide the development of models that describe the instabilities and to validate various hydrodynamic codes used at the laboratory. A number of experimental series studying hydrodynamic instabilities were carried out using Pegasus II during the last two years. One of these series, RTMIX, involves the study of the Rayleigh-Taylor (RT) instability, a phenomenon observed when acceleration occurs at an interface between two materials of different densities. The goal of these experiments is to diagnose and understand the growth of a mixing layer at an RT unstable interface and to understand the effects of material strength on the development of the mixing layer. Figure 2 shows a cross-section of the load for the first shot in this series, RTMIX 1. The liner consists of a composite cylinder with an outer 800- $\mu\text{m}$ -thick aluminum cylinder in contact with an inner 200- $\mu\text{m}$ -thick copper cylinder having an inner radius of 8 mm. The copper cylinder surrounds uniform, open-cell, polystyrene foam. The glide planes are made from a dense tungsten alloy to inhibit axial motion of the foam during the experiment.



*Fig. 2 Side-view cross-section along the mid-plane of the load for RTMIX 1. During the experiment, the portion of the liner between the tungsten glide planes separates from the rest, imploding against the foam core. The function of the glide planes is to maintain electrical contact and therefore current flow through the liner as it implodes and, for the RTMIX experiment, to inhibit axial motion of the foam as it is compressed.*

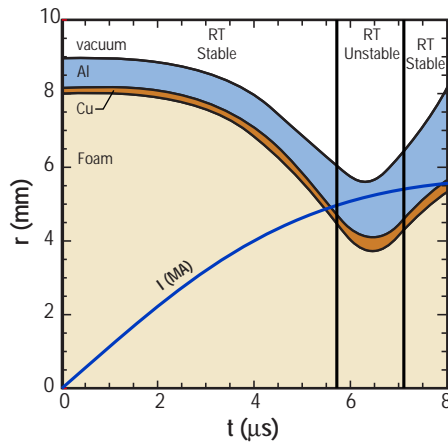


Fig. 3 1-D RAVEN simulation of an RTMIX experiment. The figure shows, as a function of time, the radius of the load interfaces and the current through the load. Also shown are the RT stable and unstable phases of the copper/foam interface.

Figure 3 shows a simulation of the experiment. The simulation is performed with RAVEN, a one-dimensional (1-D) magnetohydrodynamics (MHD) code. During the initial phase, the liner accelerates inward compressing the foam. As the compression continues, the liner decelerates, stops, and accelerates outwards—in effect, the liner bounces off the foam core. During the period of inward deceleration and outward acceleration the copper/foam interface is RT unstable. Of particular interest is the formation of a mixing layer at the copper/foam boundary as a result of the instability. The liner is designed such that the copper layer remains solid during the experiment and, therefore, it is expected that the copper's strength will play a role in the formation of a mixing layer at the interface through suppression of the instability. Analysis of the original radiographs from the RTMIX 1 experiment shows that the liner does undergo a bounce and an RT unstable phase. However, the data show no discernable evidence of a mixing layer at the copper/foam interface, which is consistent with analyses as well as two-dimensional (2-D) MHD simulations that include strength.

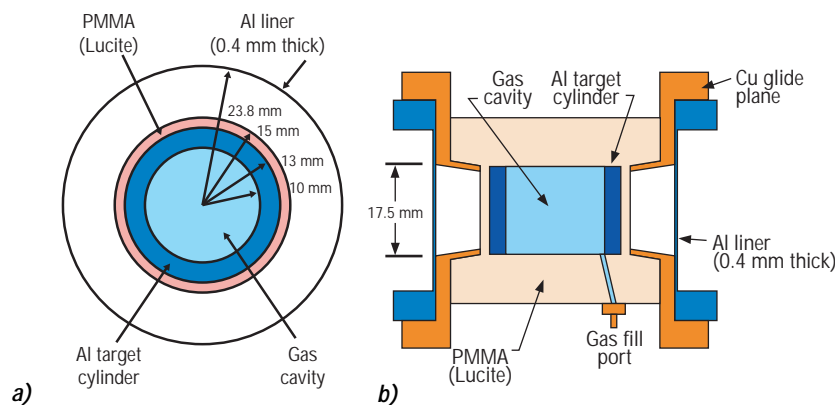
The configuration of the RTMIX 2 experiment was identical to RTMIX 1 with the exception that the inner surface of the copper cylinder had machined sinusoidal perturbations along the length of the cylinder. The perturbations had a wavelength of 1 mm and an amplitude of 50  $\mu\text{m}$  on the upper half and 12.5  $\mu\text{m}$  on the lower half of the cylinder. Analytical results and detailed 2-D MHD simulations predict that the small amplitude perturbation will not grow during the RT unstable phase of the experiment and the large amplitude perturbations will grow. However, the data show no evidence of growth of either amplitude perturbation during the experiment. The results from this experiment will be directly compared with the results from the RTMIX 4 experiment, which was conducted at the end of 1998. (Note that the numbers of the Pegasus experiments follow the order in which the loads for the experimental series are constructed, and not the shot order. The RTMIX 3 load exists, but it has not yet been fielded.) For RTMIX 4, the copper layer was replaced with a low-melting-point indium-tin eutectic alloy with the same perturbations as in RTMIX 2. It was expected that the alloy would melt during the experiment, allowing direct comparison of perturbation growth at an RT unstable interface with and without the effects of material strength. Data from RTMIX 4 are currently under analysis. Details of the RTMIX 1 and 2 experiments can be found in Sheppard, *et al.*<sup>1</sup>, and Atchison and Sheppard<sup>2</sup>.

Another experimental series performed during the past two years under the general category of hydrodynamic instabilities was a study of the vorticity and mixing generated in a target as a result of a shock-driven Richtmeyer-Meshkov (RM) instability, another hydrodynamic phenomenon associated with an interface between materials of different densities. For these experiments a standard liner was imploded onto a target generating a  $\sim 300$  kbar shock in

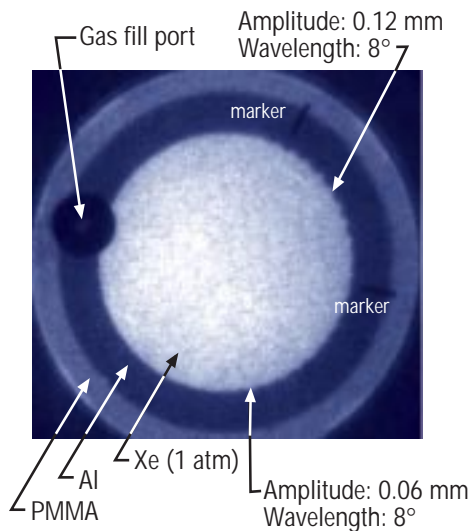
the target. Discontinuous target features seeded RM instabilities that resulted in the formation of jets and vortices. The results of these experiments are currently being employed by the computational design community to benchmark both legacy and Accelerated Strategic Computing Initiative (ASCI) hydrodynamic codes. Details of the comparisons to codes can be found in Guzik, *et al.*<sup>3</sup>.

### Material Properties

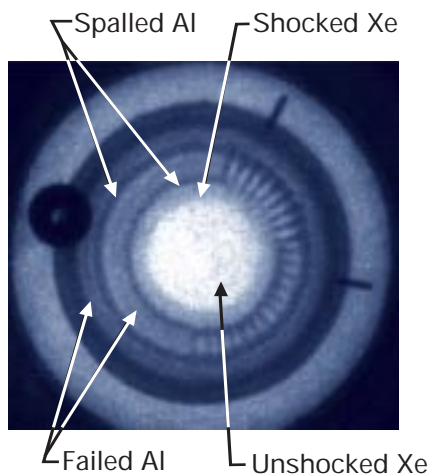
The properties of materials under extreme conditions is an area of active research at the Laboratory. A partial list of topics of interest in this category includes material failure through spall and ejecta, plastic deformations, strain and strain-rate effects, and interfacial friction. A number of experiments were carried out on Pegasus II during 1997–1998 to address various aspects of these topics. One recent series of experiments carried out in collaboration with physicists at Lawrence Livermore National Laboratory concentrated on the spallation of shocked aluminum targets. The goal of these experiments, known as the LLNL series, is to gain understanding of the failure mechanism and its role in the growth of subsequent instabilities and to investigate the role that material strength plays in these phenomena. In these experiments, a standard liner was imploded and collided with a target containing an aluminum cylinder. The collision of the liner with the target drives a shock into the target traveling toward the cylindrical axis. The resulting failure of the aluminum was recorded with multiple-frame flash radiography. Figure 4 shows a cross-section of the general target design for these experiments. The target is an aluminum cylinder with an inner radius of 1.0 cm and an outer radius of 1.3 cm surrounded by 0.2 cm of PMMA (Lucite). The



*Fig. 4 Top- (a) and side-view (b) cross-sections along the mid-planes of the liner/target design used for the LLNL series of experiments. During the experiment, current flows through the liner causing the portion between the glide planes to implode and strike the target. For several of the experiments, sinusoidal perturbations, as a function of azimuth, were machined on portions of the interior aluminum surface of the target.*



a)



b)

**Fig. 5** Axial radiographs of the LLNL-5 experiment (a) before and (b)  $3.38 \mu\text{s}$  after the liner has impacted the target. The impact velocity was  $2.2 \text{ km/s}$  resulting in a  $140\text{-kbar}$  shock in the target. In (b), the shock has exited the aluminum target and is traveling toward the center in the xenon. Visible are the boundary between shocked and unshocked xenon, layers of spalled aluminum, regions of “failed” aluminum, and jets seeded by the perturbations.

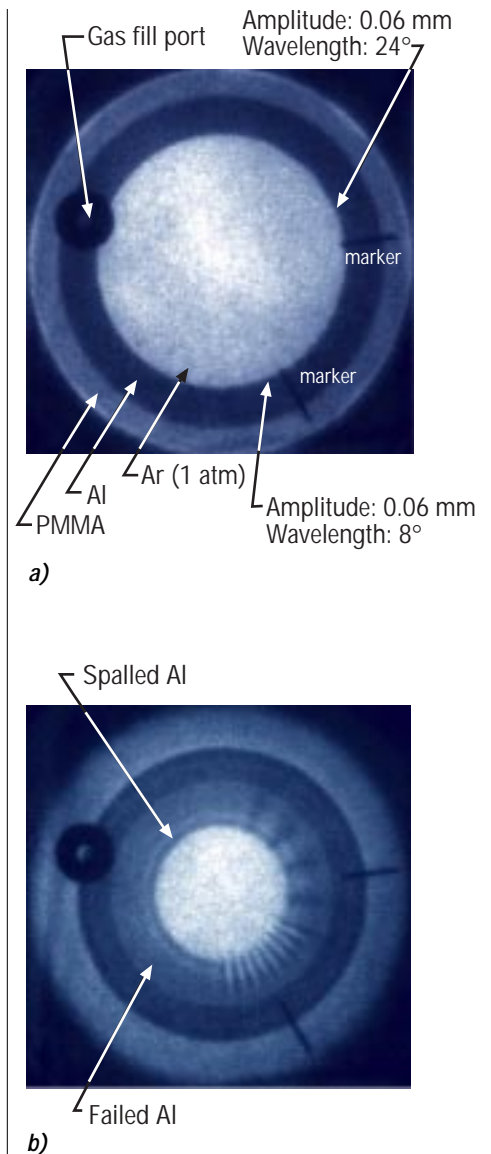
central cavity is filled with 1 atmosphere of either xenon or argon. Only a portion of the inner surface of the aluminum cylinder is smooth. Parts of the interior surface have been machined with sinusoidal perturbations, the direction, amplitude, and wavelength of which have been varied with each experiment. The purpose of the perturbations is to act as a seed for instability growth.

Figures 5 and 6 show axial radiographs of the LLNL 5 and LLNL 6 experiments both before and during the implosion. Both targets are constructed from high-yield-strength 6061-T6-series aluminum. For LLNL 5, the liner was driven such that the shock pressure in the target was  $\sim 150 \text{ kbar}$ , while for LLNL 6 the liner was driven such that the shock pressure in the target was  $\sim 500 \text{ kbar}$ . Also, there are differences in some of the machined perturbations between both targets, as can be seen from the figures. The data show both layers of spalled aluminum and regions of “failed” aluminum, the exact nature of which is still to be determined. Also shown is the growth of jets that are seeded from the perturbations. The jets form from the “valleys” of the perturbations consistent with results from modeling. Detailed comparisons of these data with data from experiments using low-yield-strength, 1100-series aluminum targets and simulations using the Livermore CALE code, an adaptive Lagrangean-Eulerian hydrodynamic code with a full implementation of the Steinberg-Guinan strength model, are currently underway. More information about these experiments with results from the initial experiments can be found in Chandler, *et al.*<sup>4</sup>

Another experimental series falling under the material properties category is focused on material strength at large strains and strain rates. With Pegasus II, strains greater than 1 and strain rates of up to  $\sim 10^6 \text{ s}^{-1}$  can be readily achieved in a material sample placed inside of an aluminum liner. In these experiments, a liner constructed of an outer layer of 1100-series aluminum and an inner layer of 6061-T6-series aluminum is imploded. The heating of the 6061-T6 layer from work done against the yield strength is measured with multichannel pyrometry. The temperature data as a function of time are unfolded to give the yield strength as a function of strain and strain rate. These experiments are providing data at conditions where none presently exists, and are being used to test the validity of strength models, some of which are employed in various hydrodynamic codes. Results from the initial experiments can be found in Bartsch, *et al.*<sup>5</sup>

Also under investigation using Pegasus II are frictional effects at shock-loaded material interfaces. For the Dynamic Friction 1 experiment, a liner was impacted on a target constructed with pie-piece-shaped wedges of aluminum and tantalum. The shock travels perpendicular to the aluminum-tantalum interfaces and, as a result of the different material characteristics of aluminum and tantalum, the shock travels faster in the aluminum resulting in a strong shear between the aluminum and tantalum. The distortion of the materials at the interface is dependent on the frictional force between the materials. The distortion in the aluminum pieces is recorded with flash radiography and the data are being compared to simulations using empirical models of interfacial friction. Also, the tantalum pieces were recovered intact and the interfaces will be subjected to microstructural analysis. Details of the Dynamic Friction 1 experiment can be found in Hammerberg, *et al.*<sup>6</sup>

A series of experiments that continued into the 1997–1998 time frame involves the study of ejecta emitted from a shocked free surface. In these experiments a standard liner is imploded, striking a 400- $\mu\text{m}$ -thick target cylinder. A shock propagates through the target cylinder reaching the inner surface, which causes ejecta to be emitted from the surface. The ejecta are imaged using holography, allowing number vs. size distribution to be determined. This work is focusing on understanding how target composition, surface finish, and shock strength affect the production of ejecta. A discussion of this series can be found in Sorenson, *et al.*<sup>7</sup>



**Fig. 6** Axial radiographs of the LLNL-6 experiment (a) before and (b) 2.14  $\mu\text{s}$  after the liner has impacted the target. The impact velocity was 4.5 km/s resulting in a 500-kbar shock in the target. In (b), the shock has exited the aluminum target and is traveling toward the center in the argon. Visible are a layer of spalled aluminum, a region of “failed” aluminum, and jets and density variations seeded by the perturbations. The shock in the argon is not visible in the radiograph due to the reduced x-ray absorption of argon.

### Basic Science and Technology

Megagauss 1 was the first in a potential series of experiments intended to use Pegasus II to generate intense magnetic fields in a macroscopic volume lasting for  $\sim 1 \mu\text{s}$ . The technique involves generating a millisecond timescale solenoidal field inside an unimploded liner with a pair of pulsed coils and then having the liner compress the field as it implodes on the microsecond timescale resulting in a magnetic field of multi-Megagauss intensity. It is expected that many electronics properties of materials should be greatly modified in the presence of such strong fields and, therefore, achieving such fields is of keen interest to the condensed matter community.

A number of experiments on Pegasus II over the last two years have been devoted to understanding the limitations of imploding a liner at near-melt conditions. Detailed 2-D MHD simulations show that under strong drive conditions the liner may break up as a result of the magnetic RT instability that occurs on the outer surface of the liner due to the magnetic field pressure pushing on the liner. Experimental data are needed to test the code predictions and have been provided by the Liner Stability (LS) series of experiments. In these experiments, the liners are radiographed during the implosion to determine the extent to which the instability has developed. For some experiments in the series, sinusoidal perturbations are machined on the outer surface of the liner to provide a known initial condition that will result in growth of the magnetic RT instability. The experimentally measured evolution of the instability can then be directly compared with code predictions using the same initial conditions. Results from the LS series can be found in Atchison, *et al.*<sup>8</sup>; Morgan, *et al.*<sup>9</sup>; and Reinovsky, *et al.*<sup>10</sup>

Los Alamos scientists have also collaborated with scientists from the All-Russian Scientific Institute of Experimental Physics (VNIIEF) in Sarov, Russia, in investigating the dynamics of liner implosion physics. Experiments with VNIIEF-designed liners are probing issues related to using materials other than 1100-series aluminum as the primary component in the liner. Details of the Russian experiments can be found in Buyko, *et al.*<sup>11</sup>

A series of experiments related to the Liner Stability and Russian experiments is addressing implosions at the maximum Pegasus II drive current of 12 MA. The motivation for the Megabar series is to develop a liner that can deliver multi-megabar shock pressures when it collides with a target. The liner consists of an 1100-series aluminum cylinder with a platinum layer on the inner surface. The aluminum carries the current and its low density allows the composite liner to achieve high velocity. The high-density platinum impactor layer results in a strong shock delivered to the target. The latest of these experiments, Megabar 3, achieved a liner velocity of  $\sim 7 \text{ km/s}$  at impact on a 1-cm radius target with minimal bleed-through of the RT instability. This configuration has the capability

of delivering a  $\sim 6$  Mbar shock to a high-density target. Results of the Megabar 1 experiment can be found in Lee, *et al.*<sup>12</sup>

A number of experiments were carried out on Pegasus II to advance the technology of mechanical joints capable of carrying high current-densities. These experiments were performed in support of Atlas, the follow-on to Pegasus, which will achieve peak currents of 32 MA. Atlas requires the ability to make reliable joints between parts that can carry current densities of up to 51 kA/cm. For this work, several configurations were tested using different materials and geometries, and the results are being used to design the high-current-density connections in Atlas. Results from this work can be found in McCuistian, *et al.*<sup>13</sup>

### **Atlas: The Next-Generation Pulsed-Power Facility**

For many applications in the nuclear weapons program and basic science, the energy of Pegasus II is insufficient to produce the conditions needed to benchmark computational predictions. These requirements have driven the development of the next-generation pulsed power driver, Atlas, now under construction. When complete in late 2000, Atlas will be a 23-MJ capacitor bank, capable of delivering over 30 MA of current to liner targets with a nominal 4- $\mu$ s rise-time. The machine will consist of 12 pulsed-power modules, each driving a transmission line. All 12 transmission lines connect to a central powerflow channel, which provides a symmetric delivery of current to the target. The target will be contained inside a 2-m-diameter vacuum chamber. At the end of 1998, the final design of the machine was complete with many subsystems tested and many major components on order. When complete, the pulsed power system will be approximately 80 ft in diameter, and it will be supported by a suite of mechanical systems, controls, diagnostics, and data acquisition systems.

Atlas will deliver 2–5 MJ of kinetic energy to nominal 8-cm-diameter, 50-g liners, making possible many new experiments in dynamic materials properties and hydrodynamics. Many candidate experiments have now been identified and are being studied computationally. Among materials properties experiments of interest are absolute equation-of-state measurements along the Hugoniot up to 20 Mbar and along the adiabat up to 5–10 Mbar. Both of these experiments will represent significant extensions of present capabilities. We are also designing hydrodynamic experiments with strongly coupled plasmas (plasmas in which the strength of the electrostatic potential of the ions is comparable to or greater than their thermal energy), for which very little prior experimental or theoretical understanding exists. A key feature of these experiments is that the high kinetic energy of Atlas will enable us to create an experimental region large enough that diagnostics can easily resolve hydrodynamic details. Other experiments under development include extension of the high-strain-rate, dynamic friction, and spallation experiments presently

being conducted at Pegasus. Atlas should also provide interesting experimental environments for basic science. For example, generation of magnetic fields up to 2,000 T (20 MG) should be possible. In such fields, the cyclotron radius of a valence electron in a metal is reduced to less than the interatomic spacing, thus involving entirely new mechanisms of electron transport in condensed matter.

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